Vibrotactile Navigational Cues Can Be Effective for Specific Urban Air Mobility Operations

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Abstract. Urban air mobility (UAM) operations will require precise navigation in high workload conditions. This study examined how vibrotactile navigational cues impact UAM flight performance and operator experience. Novice participants piloted a simulated UAM aircraft along predetermined routes in a virtual reality simulation of the San Francisco metropolitan area. In some trials, vibrotactile cues alerted participants to horizontal and vertical flight path deviations. Each participant completed three simulation runs, consisting of en-route and glideslope landing operations with each cue type (directional, nondirectional, no cues). Objective measures (trial time, path deviation frequency, correction time), subjective ratings (workload, situational awareness, system usability), and post-experiment feedback were collected. During the en-route phase, participants exhibited shorter correction times using directional and nondirectional cues compared to no cues. Fewer path deviations were observed within directional cues trials during both en-route and glideslope landing operations compared to nondirectional and no cues. While directional cues did not improve situational awareness, they also did not increase workload or reduce usability scores. In contrast, nondirectional cues improved situational awareness but also increased workload, lowered usability scores, and reduced performance. These results suggest directional vibrotactile navigational cues could enhance multimodal UAM displays by providing intuitive, nonvisual guidance during different flight operations.

Keywords: Urban Air Mobility, Tactile Navigational Feedback

1 Introduction

1.1 Urban Air Mobility (UAM)

Urban Air Mobility (UAM) refers to an on-demand transportation system for delivering passengers and cargo in crowded cities (FAA, 2023; Thipphavong et al., 2018). UAM is expected to relieve demand for ground-based infrastructure and increase human mobility as urban populations continue to rise (Antcliff et al., 2016). Despite its promise, many human factors issues related to UAM remain unaddressed (Al Haddad et al., 2020; Lu et al., 2011; Strybel et al., 2024). For instance, advanced UAM conceptualizations will rely mostly on autonomous systems; however, near-term operations are likely to employ onboard, or remote, operators flying UAM vehicles under current-day visual or instrument flight rules. Moreover, vertical take-off and landing (VTOL) has been proposed for UAM operations, but VTOL is not efficient for the air traffic management of multiple aircraft landing at vertiports. Thus, there are still many concepts and procedures that need to be evaluated for UAM.

These operational challenges will likely exacerbate a known UAM implementation constraint, the scalability of the current air traffic control (ATC) system (Lascara, 2019; Nguyen, 2020; Vascik & Hansman, 2018). To address this, dynamic delegated corridors (DDCs) which provide adaptable flight paths managed in real time are anticipated to be used in UAM operations. Although minimum performance requirements for UAM DDCs have not been established, they will likely demand precision flying. Based on Fédération Aéronautique Internationale (FAI) standards, preliminary thresholds for UAM navigation suggest a horizontal error radius around the intended flight path of 15 meters for standard operations and 3 meters for precision operations, with vertical limits of 30 meters (standard) and 15 meters (precision) (Bijjahalli et al., 2019). To achieve this level of accuracy, operators may require navigational cues beyond those provided by typical flight instruments used in instrument flight rules operations (Bijjahalli et al., 2019).

1.2 Tactile Navigational Cues

Tactile navigational cues present a promising solution for supporting the navigational performance of operators in high-workload environments. Research shows that tactile cueing can help overcome perceptual bottlenecks, particularly when visual and auditory resources are overwhelmed (van Erp et al., 2017). These cues have been found to enhance spatial situational awareness and improve navigational performance across a range of tasks (see Meng & Spence, 2015; Lu et al., 2011). For instance, directional tactile cues have been shown to reduce absolute path deviation by 50% without increasing mental workload (van Erp, 2007). In visually degraded flight environments, tactile feedback enabled faster and more accurate corrections of aircraft drift and was associated with significantly higher situational awareness (Rupert, 2000). While tactile cueing has been widely studied in both basic and applied contexts, its potential remains underexplored in the specific domain of UAM operations.

1.3 Present Study

In the present study, en route and landing procedures for UAM are tested. For the en route phase, we propose that UAM operators follow freeway corridors, using existing highways as visual landmarks to navigate toward designated vertiports. For landing, we propose using a glideslope approach as it requires less air traffic coordination, offers efficient aircraft power management, and is better for passenger comfort. To support operators in meeting minimum DDC performance requirements, we propose the use of tactile navigational cues during both en route and landing phases of flight. Specifically, the impact of directional and nondirectional vibrotactile cues on vertical and horizontal path navigation at various phases of flight is tested.

This experiment stems from a larger program of research which investigates UAM technologies and concepts of operations using 3D virtual reality simulation tools in the BeachCAVE Laboratory at California State University, Long Beach (see Fig. 1). Use of the simulation as a testbed, simplified vehicle operations, and advanced automations for UAM operations have previously been tested (Ahuja et al., 2023; Haneji et al., 2023; Strybel et al., 2022; Strybel et al., 2024). The virtual environment depicts potential scenarios for UAM operations and vertiport locations in the San Francisco metropolitan area. Participants operated a simulated aircraft which is modeled after a VTOL quadcopter.

In line with previous research, it is hypothesized that directional vibrotactile cueing will enhance UAM operator performance, increase situational awareness, and reduce perceived workload by providing immediate intuitive feedback on flight deviations. Ultimately, the results of this study will further explain the role of vibrotactile cueing in multimodal UAM aircraft displays and offer valuable insights for improving their design.

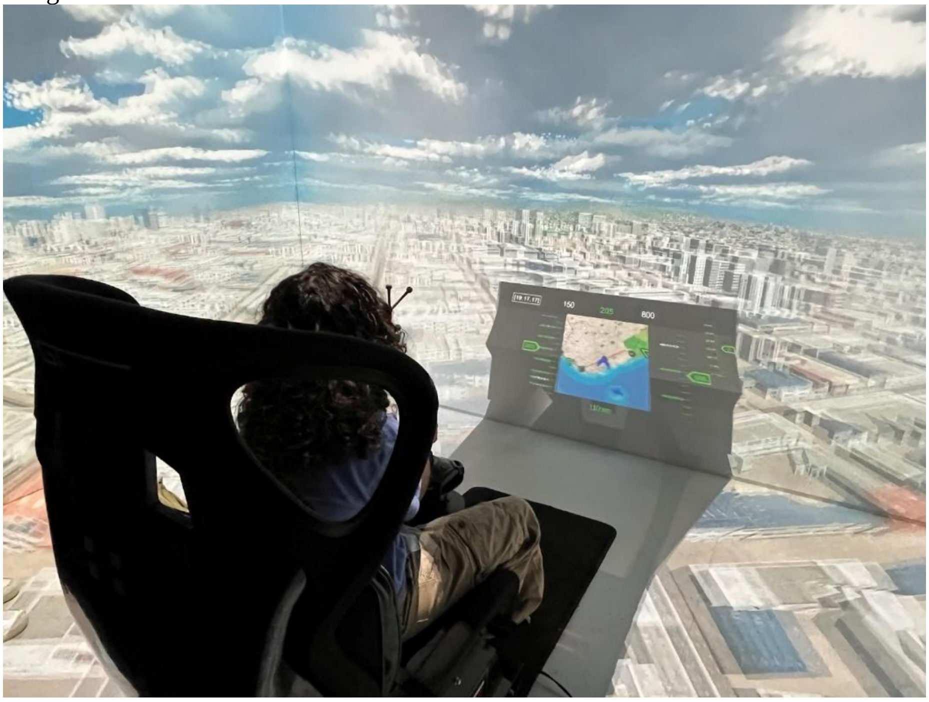

Fig. 1. View of the virtual environment.

2 Method

2.1 Participants

Novice participants with no prior flight training were recruited for the present study to examine the effectiveness of vibrotactile cues rather than to evaluate future concepts of operation. A total of 24 participants (7 female, 17 male, MAGE = 26 yrs, SDAGE = 9 yrs) completed the study.

2.2 Simulation Facility

The virtual environment, depicting the San Francisco Bay Area, was presented using a 3-D cave system (see Fig. 1). The virtual UAM quadcopter base model was purchased through the Unity Asset Store (Unity Technologies, Inc.) and adapted using Blender (Community, 2018; Haas, 2015). Participants wore 3-D glasses with head tracking technologies and functions to adjust the virtual environment to their perspective. The cockpit displays and instrument dimensions were set to adhere to the point of view of a stationary seated operator. For an overview of the system's development, design of the simulated UAM aircraft, and design of the test environment, see Marayong et al. (2020) and Shankar et al. (2022).

Participants assumed manual control of a simplified quadcopter UAM aircraft and controlled all flight parameters using a joystick (see Fig. 2). A script was written to enable real-time user control of the aircraft via joystick. Participants adjusted aircraft forward speed, rate of acceleration, altitude, rate of ascent, and heading. The joystick flight control arrangement was designed to imitate single joystick simplified vehicle operation (SVO) as described in Wing et al. (2020) and based on NASA's EZ-Fly Concept for simplifying vertical takeoff and landing flight handling.

The virtual cockpit display (see Fig. 3) contained an instrument panel which displayed flight parameter values: target speed, current speed, desired speed (for use during glideslope landing), heading, target altitude, current altitude, desired altitude (for use during glideslope landing), and rate of ascent. The instrument panel featured a dynamic minimap which displayed an overhead view of the flight environment, aircraft indicator, vertiport location, flight route (orange line), and map markers (grey circle which indicates top of descent location). The instrument panel also housed a glideslope display which showed the altitude (y axis) and distance in nautical miles (x axis) of waypoint fixes and the closest vertiport. The glideslope display was meant to facilitate glideslope landings, featuring the ideal glideslope angle (magenta line) and a dynamic noodle (white line extruding from the aircraft icon) which showed the anticipated trajectory of the aircraft based on current flight parameters.

Fig. 2. Joystick.

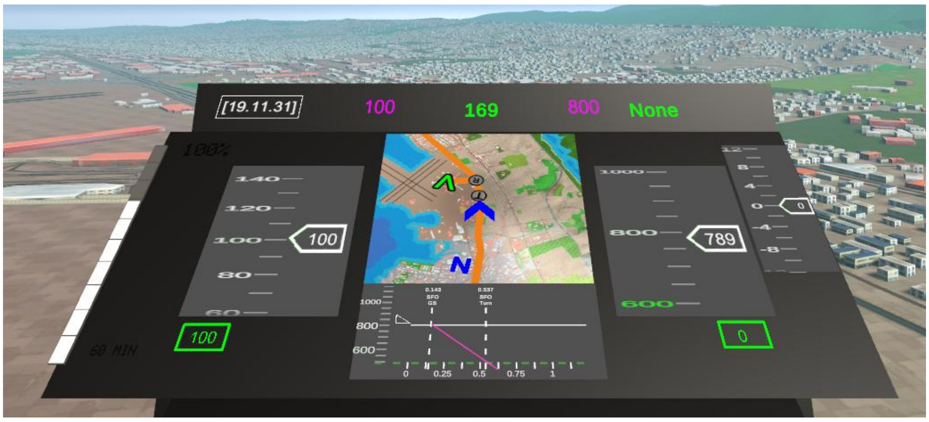

Fig. 3. Cockpit display and instrument panel.

2.3 Tactors

Participants were presented vibrotactile cues via four tactors arranged in a diamond shaped array (see Fig. 4). The array was placed on the back of the torso and centered along the spine. The number of tactors, array configuration, and placement on the body were chosen to ensure sensitivity to tactor location and accommodate a broad range of vibratory stimuli intensities (Cholewiak, 2004; Jones et al., 2006; Jones et al., 2008; Van Erp, 2007). Additionally, the diamond configuration was spatially compatible with the vertical and horizontal corrective actions they cued. Vibratory intensity levels were kept consistent between the directional and nondirectional cue conditions.

In the directional cue condition, the left and right tactors provided left and right horizontal cues, respectively. In this condition, the tactors alerted when a participant deviated from the intended horizontal flight path by more than 15 meters from the center of the flight path (most relevant for the en route phase). The top and bottom tactors provided up and down vertical cues, respectively. The tactors alerted when a participant deviated from the intended vertical flight path by more than 15 meters from the designated altitude (most relevant for the glideslope landing phase). In the nondirectional cue condition both the left and right tactors alerted simultaneously to indicate a horizontal path deviation of more than 15 meters from the center of the flight path. The top and bottom tactors alerted simultaneously to indicate a vertical path deviation of more than 15 meters from the designated altitude. In the no cues condition, the tactors did not alert when a participant deviated from the horizontal or vertical flight path. Participants experienced the tactor alerts prior to the experimental trials and were able to correctly identify the location of the activated tactor(s) and their meaning. Participants completed three flights, each featuring one of three cue conditions: Directional, nondirectional, or no vibrotactile navigational cues.

Fig. 4. Tactor array.

2.4 Scenario

Participants flew on predetermined routes over major freeways/streets between the Oakland International Airport (OAK) and Hayward Executive Airport (HWD) (see Fig. 5). These vertiport locations were chosen as they are currently being considered for use in UAM operations. The route was chosen to ensure a level of navigational complexity while maintaining position over existing streets and highways that are also visible on the minimap and out-the-window view of the aircraft in the simulation. Each flight consisted of three flight phases: Vertical ascent, en route, and landing using a glide-slope approach. The procedure resulted in a total of three flights with cue type and starting vertiport counterbalanced to control for order and practice effects.

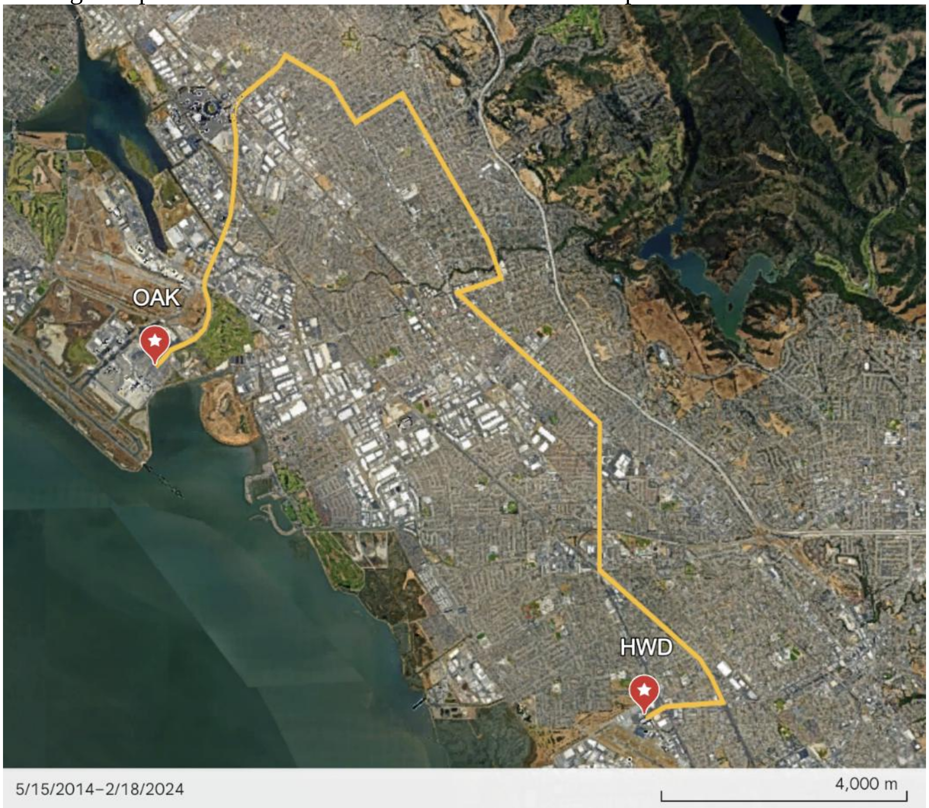

Fig. 5. Flight route.

2.5 Measures

Performance and self-reported measures of perceived workload, situational awareness, and system usability were recorded. Performance was quantified by correction time, frequency of path deviations, and total trial time. Correction time measurements started at tactor activation, triggered when the aircraft's deviation exceeded 15 meters horizontally from the center of the designated flight path or 15 meters vertically from the assigned altitude. Correction time measurements ended at tactor deactivation, which occurred when the aircraft returned within this threshold. Deviation frequency was counted as the number of times the aircraft exceeded the performance limiting threshold. Total trial time was measured from the time the aircraft reached its target altitude to the moment of touch down on the vertiport landing pad. The Situational Awareness Rating Technique (SART), NASA TLX, Modified Cooper-Harper, and System Usability Scale (SUS) were administered after each trial (Cooper & Harper, 1969; Hart & Staveland, 1988; Stanton & Young, 1999; Taylor, 1990). Finally, post-experiment Likert-scale questions were administered after the experiment to gauge user sentiment of the vibrotactile displays.

3 Results

Initially, a 3 (Cue Type: Directional / Nondirectional / No Cues) x 2 (Flight Phase: En Route / glideslope) repeated measures ANOVA was planned to investigate how directional, nondirectional, and no vibrotactile navigational cues affected correction time and deviation frequency during various phases of flight. However, a Levene's Test revealed a significant difference in variances across flight phases, violating the assumption of homogeneity of variances required for the ANOVA ($F(1, 70) = 33.47$, $p < .001$) and $F(1, 70) = 27.94$, $p < .001$ respectively.

Data from 12 participants (50%) were excluded from the glideslope performance analyses because they did not complete the glideslope landing. Specifically, 7 participants (29.17%) were excluded because they landed off of the vertiport landing pad (i.e. on the ground elsewhere), 3 participants (12.5%) were excluded because they crashed during the approach (i.e. into a building or on the ground), 1 participant (4.17%) was excluded because the simulation unexpectedly terminated during the approach, and 1 participant (4.17%) was excluded because they were confused by the display and did not engage in the glideslope approach. The final data set used for glideslope analyses consisted of the remaining 12 participants.

3.1 Performance Measures

Total Trial Time. A one-way (Cue Type: Directional / Nondirectional / No Cues) repeated measures ANOVA was conducted to investigate how total trial time, from reaching target altitude to touchdown at the vertiport landing pad, differed when using directional, nondirectional, and no navigational vibrotactile cues (see Fig. 6). The main effect of cue type was not significant, $F(2, 22) = 0.68$, $p = .515$, $\eta_p^2 = .059$.

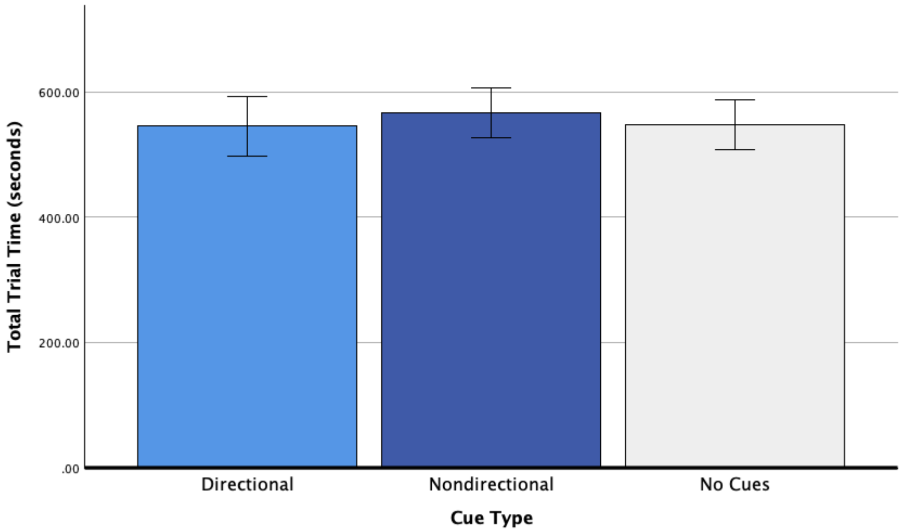

Fig. 6. Total trial time by cue type. Error bars represent ±2 standard errors of the mean.

En Route Flight Phase.

Correction Time. A one-way (Cue Type: Directional / Nondirectional / No Cues) repeated measures ANOVA was conducted to investigate how directional, nondirectional, and no vibrotactile navigational cues affected correction time during the en route flight phase (see Fig. 7). Using the Greenhouse-Geisser correction, the main effect of cue type was significant, $F(1.33, 30.55) = 24.23$, $p < .001$, $\eta_p^2 = .52$. Applying a Bonferroni correction, correction time when using directional cues ($M = 6.99$ s, $SD = 3.31$ s) ($p < .001$) and nondirectional cues ($M = 7.67$ s, $SD = 3.02$ s) ($p < .001$) was significantly shorter than when using no cues ($M = 13.29$, $SD = 6.17$). However, correction times for directional and nondirectional cues did not significantly differ from each other.

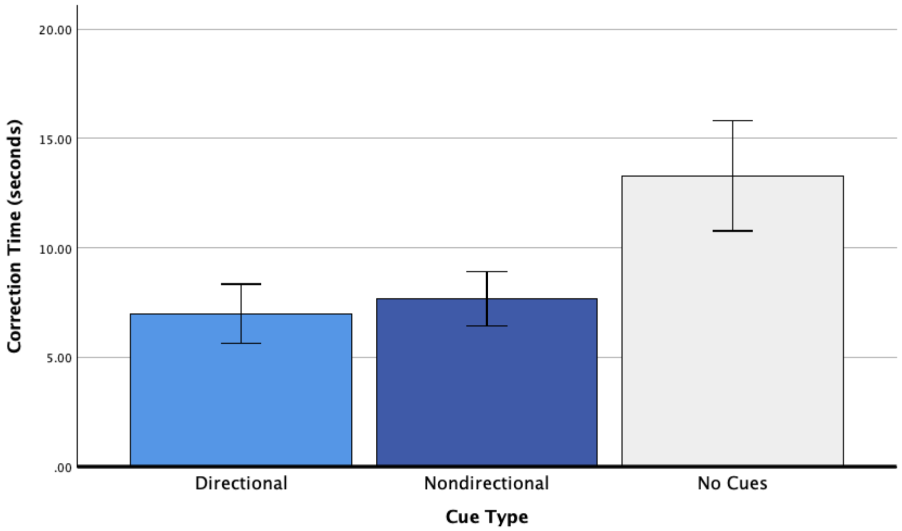

Fig. 7. Correction time by cue type during en route flight phase. Error bars represent ±2 standard errors of the mean.

Deviation Frequency. A one-way (Cue Type: Directional / Nondirectional / No Cues) repeated measures ANOVA was conducted to investigate how directional, nondirectional, and no vibrotactile navigational cues affected the frequency of vertical and horizontal deviations from the flight path during the en route flight phase (see Fig. 8). Using the Greenhouse-Geisser correction, the main effect of cue type was significant, $F(2.0, 45.93) = 47.52$, $p < .001$, $\eta_p^2 = .67$. Applying a Bonferroni correction, significantly fewer path deviations occurred when using directional cues ($M = 29.88$, $SD = 6.37$) compared to nondirectional ($M = 53.50$, $SD = 11.75$) ($p < .001$) and no cues ($M = 40.25$, $SD = 8.75$) ($p < .001$). Additionally, significantly fewer path deviations occurred when using no cues compared to nondirectional cues ($p < .001$).

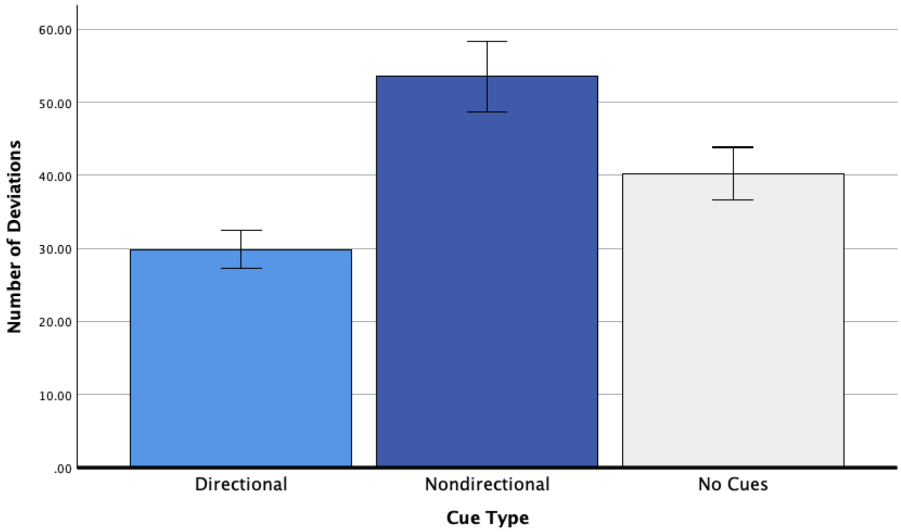

Fig. 8. Deviation frequency by cue type during en route flight phase. Error bars represent ±2 standard errors of the mean.

Glideslope Flight Phase.

Correction Time. A one-way (Cue Type: Directional / Nondirectional / No Cues) repeated measures ANOVA was conducted to investigate how directional, nondirectional, and no vibrotactile navigational cues affected correction time during the glideslope flight phase (see Fig. 9). The main effect of cue type was not significant, $F(2, 22) = 0.96$, $p = .400$, $\eta_p^2 = .08$.

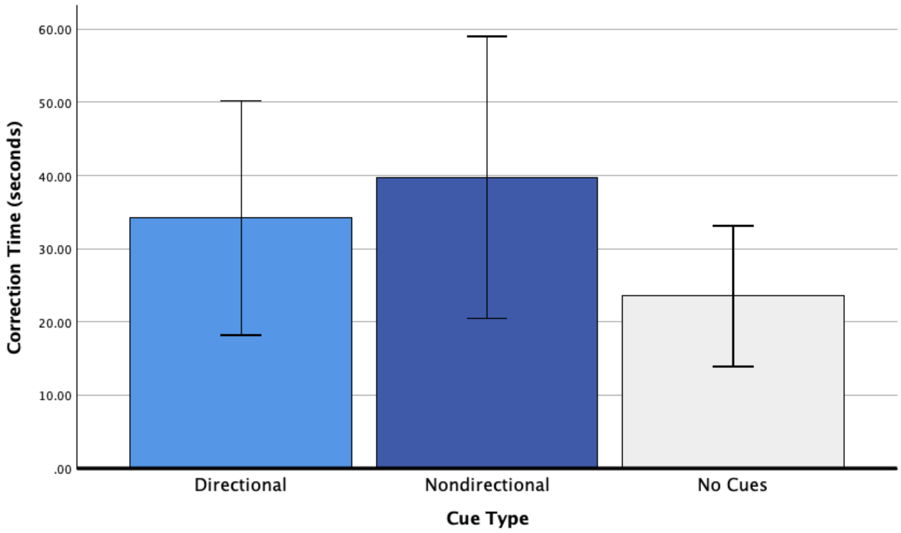

Fig. 9. Correction time by cue type during glideslope flight phase. Error bars represent ±2 standard errors of the mean.

Deviation Frequency. A one-way (Cue Type: Directional / Nondirectional / No Cues) repeated measures ANOVA was conducted to investigate how directional, nondirectional, and no vibrotactile navigational cues affected the frequency of vertical and horizontal deviations from the flight path during the glideslope flight phase (see Fig. 10). The main effect of cue type was significant, $F(2, 22) = 5.041$, $p = .016$, $\eta_p^2 = .314$. Applying a Bonferroni correction, significantly more path deviations occurred when using no cues ($M = 5.83$, $SD = 3.13$) than when using directional cues ($M = 2.67$, $SD = 1.61$) ($p = .044$). However, the frequency of path deviations when using directional and nondirectional cues was not significantly different. Additionally, the frequency of path deviations when using nondirectional cues and no cues was not significantly different.

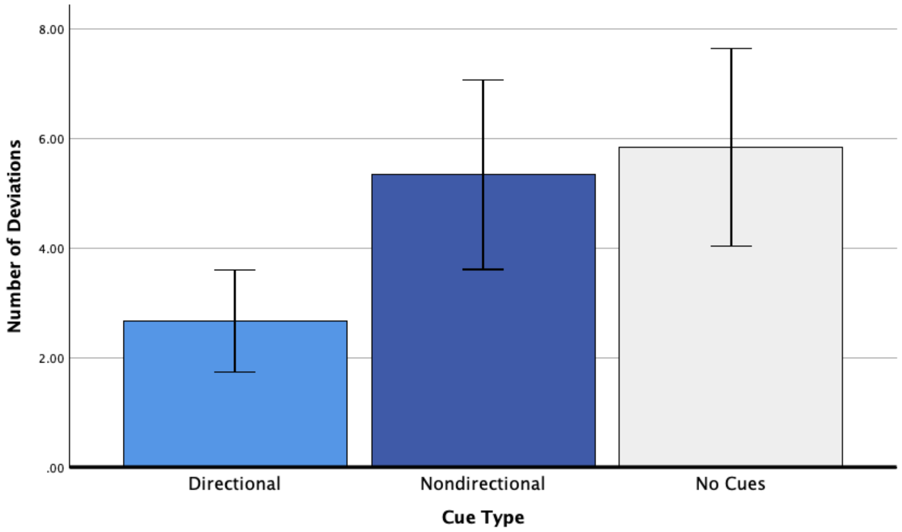

Fig. 10. Deviation frequency by cue type during glideslope flight phase. Error bars represent ±2 standard errors of the mean.

3.2 Subjective Measures

NASA Task Load Index (NASA TLX).

A one-way (Cue Type: Directional / Nondirectional / No Cues) repeated measures ANOVA was conducted to investigate how directional, nondirectional, and no vibrotactile navigational cues affected reported workload scores (see Fig. 11; see Table 1). The main effect of cue type was significant, $F(2, 46) = 5.77$, $p = .006$, $\eta_p^2 = .20$. Bonferroni pairwise comparisons showed that workload scores for the nondirectional cue condition ($M = 50.87$, $SD = 18.11$) were significantly greater than those obtained for the no cues condition ($M = 38.82$, $SD = 16.81$) ($p = .012$). The workload scores for the directional cues ($M = 44.31$, $SD = 17.20$) were not significantly different from those found in the nondirectional or no cue conditions.

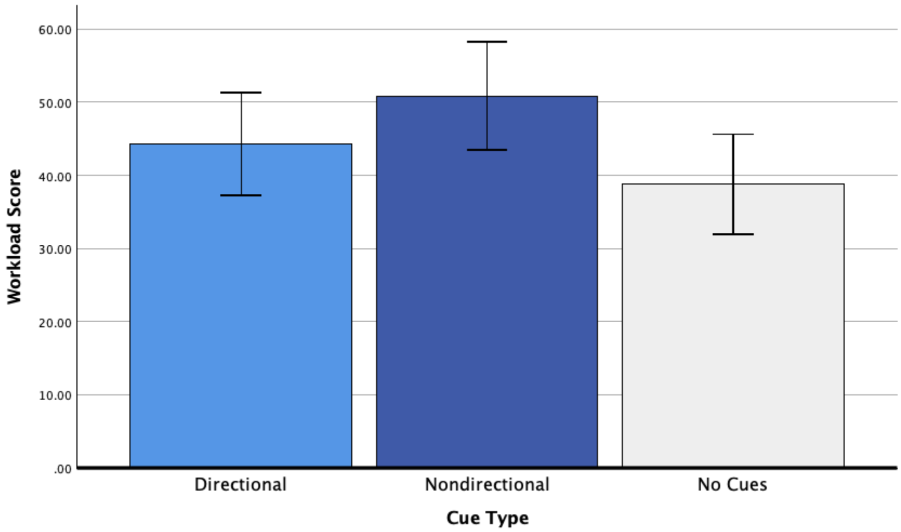

Fig. 11. NASA TLX scores. Error bars represent ±2 standard errors of the mean.

Situational Awareness Rating Technique (SART).

A one-way (Cue Type: Directional / Nondirectional / No Cues) repeated measures ANOVA was conducted to investigate how directional, nondirectional, and no vibrotactile navigational cues affected composite SART scores (see Fig. 12; see Table 1; Taylor, 1990). The main effect of cue type was significant, *F*(2, 46) = 4.68, *p* = .014, $\eta_p^2 = .169$. Bonferroni pairwise comparisons showed that SART scores for nondirectional cues (*M* = 4.57, *SD* = 0.84) were significantly higher than for no cues (*M* = 4.11, *SD* = 0.71) (*p* = .005). SART scores for directional cues (*M* = 4.17, *SD* = 0.70) were not significantly different from those found in the nondirectional or no cue conditions.

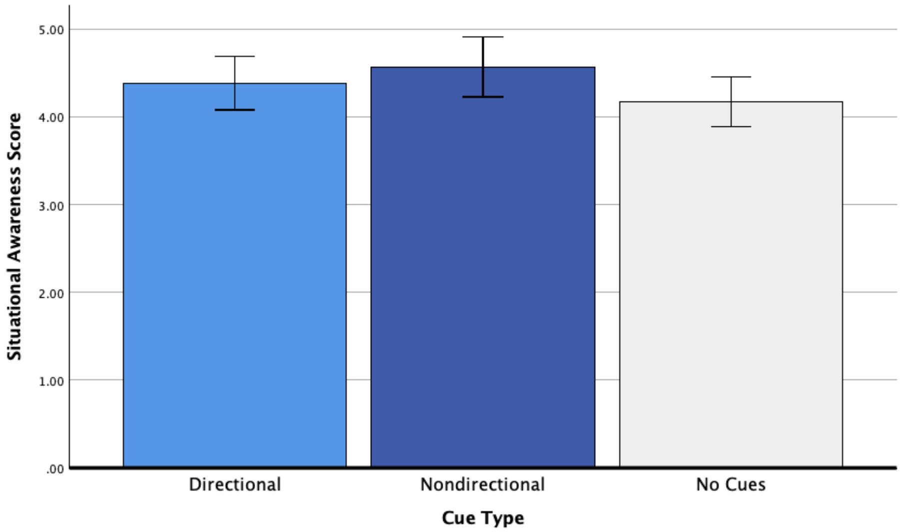

Fig. 12. SART scores. Error bars represent ±2 standard errors of the mean.

System Usability Scale (SUS).

A one-way (Cue Type: Directional / Nondirectional / No Cues) repeated measures ANOVA was conducted to investigate how directional, nondirectional, and no vibrotactile navigational cues affected reported system usability scores (see Fig. 13; see Table 1). Using the Greenhouse-Geisser correction, the main effect of cue type was significant, $F(1.63, 37.50) = 7.79$, $p = .003$, $\eta_p^2 = .25$. Bonferroni pairwise comparisons showed that participants reported significantly higher SUS when directional cues (M = 66.15, SD = 14.45) were employed compared to when nondirectional cues (p = .038) were employed. Additionally, SUS scores were significantly higher for the no cues condition (M = 67.29, SD = 15.46) compared to the nondirectional cue condition (M = 57.50, SD = 17.77) (p = .005). The difference in SUS scores for directional cues and no cues were not significantly different.

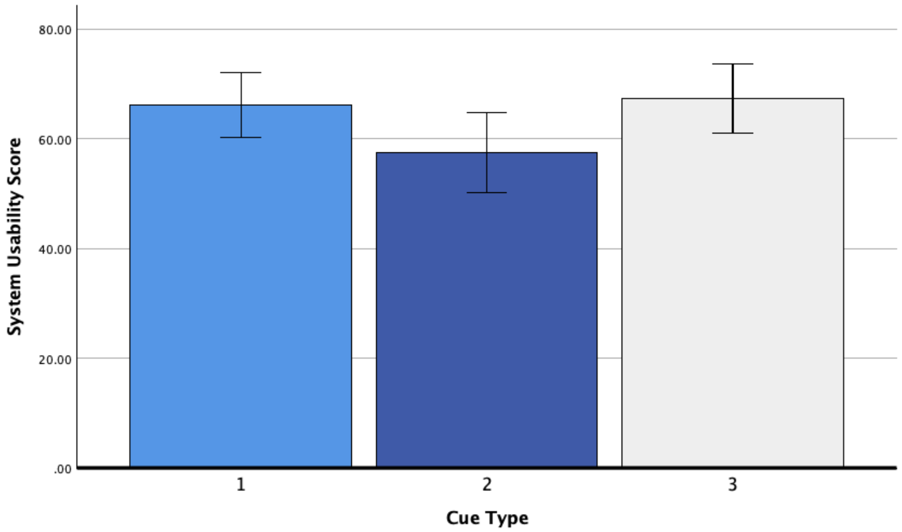

Fig. 13. SUS scores. Error bars represent ±2 standard errors of the mean.

Table 1. Workload (NASA TLX), Situational Awareness (SART), System Usability (SUS) Scores. (SEM) stands for standard error of the mean.

Cue Type	NASA TLX Mean (SEM)	SART Mean (SEM)	SUS Mean (SEM)
Directional	44.31 (17.20)	4.17 (0.70)	66.15 (14.45)
Nondirectional	50.87 (18.11)	4.57 (0.84)	57.50 (17.77)
No cues	38.82 (16.81)	4.11 (0.71)	67.29 (15.46)

3.3 Post-Experiment Feedback

A post-experiment questionnaire evaluating the vibrotactile cueing display was administered. Written explanations for ratings were also collected. Dimensions of comfort, placement, understandability, helpfulness, and distractibility were measured on a Likert-like scale with anchors ranging from 1 (Low or Did Not Understand or Not Helpful or Not Distracting) to 7 (High or Understood Well or Helpful or Distracting). One-sample t-tests were conducted to determine whether participants' ratings differed significantly from the neutral midpoint of the scale (4) (see Table 2).

Rate the comfort of the vibrations during the experiment. The one-sample t-test was not statistically significant, $t(23) = 1.79$, $p = .087$, indicating that these ratings did not differ significantly from neutral ($M = 4.63$, $SD = 1.71$).

“The vibrations were not uncomfortable, but I did feel myself getting overstimulated by the sensation. Especially when I was landing.” - Participant 14

Rate the placement of the vibrations during the experiment. The one-sample t-test was not statistically significant, $t(23) = 0.32$, $p = .753$, indicating that these ratings did not differ significantly from neutral ($M = 4.08$, $SD = 1.28$).

“Placement further apart would aid with discrimination. Different frequencies for left/right versus up/down would help.” - Participant 10

Rate the intensity of the vibrations during the experiment. The one-sample t-test was not statistically significant, *t*(23) = 0.83, *p* = .417, indicating that these ratings did not differ significantly from neutral (*M* = 4.25, *SD* = 1.48).

“The vibration was a higher frequency than I would have liked. I think it made it more ticklish. It felt urgent (maybe it is). It would be interesting if the vibration increased in frequency based on how far you deviated from the path.” - Participant 19

How well did you understand the meaning of the directional display. The one-sample t-test was statistically significant, *t*(23) = 10.48, *p* < .001, indicating that these ratings were significantly higher than neutral (*M* = 6.08, *SD* = 0.97).

“Directional provided useful information and less thinking. Nondirectional tells me something is off, but no solution. Directional vibrations were more distinct than nondirectional.” - Participant 20

How well did you understand the meaning of the nondirectional display. The one-sample t-test was significantly significant, *t*(23) = 2.93, *p* = .007, indicating that these ratings were significantly higher than neutral (*M* = 5.17, *SD* = 1.95).

“The nondirectional vibrations were confusing. I had to go both directions to figure out what I was doing wrong.” - Participant 18

Rate how helpful the directional display was while flying on the route. The one-sample t-test was statistically significant, *t*(23) = 10.02, *p* < .001, indicating that these ratings were significantly higher than neutral (*M* = 6.00, *SD* = 0.98).

“Felt natural to follow it.” - Participant 3

Rate how helpful the nondirectional display was while flying on the route. The one-sample t-test was not statistically significant, *t*(23) = -1.81, *p* = .083, indicating that these ratings did not differ significantly from neutral (*M* = 3.50, *SD* = 1.35).

“It wasn't clear what I should do next, I have to scan the interface to determine the direction I should fix.” - Participant 6

Rate how helpful the directional display was for landing. The one-sample t-test was not statistically significant, *t*(23) = -0.39, *p* = .701, indicating that these ratings did not differ significantly from neutral (*M* = 3.83, *SD* = 2.10).

“For glideslope, I paid more attention to the desired speed and climb/descend rate.” - Participant 2

Rate how helpful the nondirectional display was for landing. The one-sample t-test was statistically significant, *t*(23) = -7.45, *p* < .001, indicating that these ratings were significantly lower than neutral (*M* = 2.25, *SD* = 1.15).

“Helpful to a certain extent, but are overwhelming and I crashed anyway.” - Participant 14

Rate how distracting the directional display was. The one-sample t-test was statistically significant, *t*(23) = -3.14, *p* = .005, indicating that these ratings were significantly lower than neutral (*M* = 2.96, *SD* = 1.63).

“They were very noticeable but not super distracting unless I was very off course.” - Participant 16

Rate how distracting the nondirectional display was. The one-sample t-test was not statistically significant, $t(23) = 0.11$, $p = .914$, indicating that these ratings did not differ significantly from neutral ($M = 4.04$, $SD = 1.88$).
“Since these didn't provide very specific feedback it took longer to adjust and get rid of the buzzing, so I was mainly focused on the vibrations.” - Participant 24

Table 2. Post-experiment Likert-scale scores. Asterisks indicate values significantly different from the neutral midpoint of the scale (4) based on two-tailed one-sample t-tests ($p < .01$). (SD) stands for standard deviation of the mean.

Question	Mean (SD)
Rate the comfort of the vibrations during the experiment.	4.63 (1.71)
Rate the placement of the vibrations during the experiment.	4.08 (1.28)
Rate the intensity of the vibrations during the experiment.	4.25 (1.48)
How well did you understand the meaning of the directional display?	6.08 (0.97) *
How well did you understand the meaning of the nondirectional display?	5.17 (1.95)
Rate how helpful the directional display was while flying on the route.	6.00 (0.98) *
Rate how helpful the nondirectional display was while flying on the route.	3.50 (1.35)
Rate how helpful the directional display was for landing.	3.83 (2.10)
Rate how helpful the nondirectional display was for landing.	2.25 (1.15) *
Rate how distracting the directional display was.	2.96 (1.63) *
Rate how distracting the nondirectional display was	4.04 (1.88)

4 Discussion

As hypothesized, participants exhibited shorter correction times when using directional and nondirectional vibrotactile cues compared to the no cues condition. Though, this effect was limited to the en route flight phase, with no significant differences being found in the glideslope flight phase. Correction times during the glideslope phase showed a nonsignificant trend toward greater variability and longer durations when using directional and nondirectional cues compared to the no cues condition. The longest correction times were found in the nondirectional cue condition. Post-experiment feedback may help explain these findings. In open-ended responses, participants stated that the nondirectional cues prompted them to consult the cockpit display or virtual environment to determine the appropriate correction direction. This meant that extra time was required for participants to process the cue, refer to the display to gather information, make a judgement as to which way to correct, and initiate that action.

Significantly fewer flight path deviations occurred during the en route phase when using directional cues compared to the nondirectional and no cue conditions: with the highest average number of deviations being present in the nondirectional cue condition. Again, post-experiment feedback may expand on these findings. In open-ended responses, participants reported that because the nondirectional cues did not convey which direction to correct, they sometimes corrected the wrong way. This meant the aircraft was further from the intended flight path and an even harsher correction was required to return. Participants further explained that harsher corrections sometimes caused them to overshoot the flight path, and this may have led to further deviations. Finally, in the glideslope phase, fewer path deviations occurred in the directional cue condition compared to nondirectional and no cue conditions. This indicates that directional cues may have contributed to improved landing performance, and future work should be done to parse why these cues did not have a similar effect on correction time.

Self-reported workload scores suggest that directional cues did not increase perceived workload or decrease perceived system usability; however, they also failed to enhance situational awareness as originally hypothesized. Given that previous studies have demonstrated that tactile feedback can improve situational awareness, further research should explore how the directional cues could be modified to better support situational awareness (Rupert, 2000). Notably, participants did report higher situational awareness when using nondirectional cues compared to no cues; however, they also experienced increased workload, decreased perceived system usability, and lower overall performance. These findings are further supported by participant feedback, which characterized directional cues as intuitive, helpful, and non-distracting.

The combined results support previous notions that vibrotactile feedback is an effective tool for increasing performance in flight navigation tasks (Rupert, 2000; van Erp, 2007). Ultimately, performance was best in the directional cue condition during both the en route and glideslope flight phases. The one caveat being non significantly high correction times and increased variability during the glideslope landing phase.

While the purpose of this study was not to test the specifics of tactile feedback display designs, considerations will be provided. For one, participants suggested modifying the intensity of the vibrotactile cues based on the magnitude of deviation from the intended flight path (i.e., lower frequency for minor deviations and higher frequency for larger deviations). Such adjustments could provide additional navigational information by indicating the extent of the required correction. This recommendation is in line with previous studies that have shown higher vibration intensities are associated with greater perceived urgency and faster response times (Meng & Spence, 2015). Moreover, some participants noted that the directional cues initially felt unintuitive, reporting that their first instinct was to move the aircraft in the opposite direction of the cue. This mental model aligns with the design of many existing hazard avoidance systems. Although prior basic and applied research does not support the use of spatially incompatible cueing for navigational tasks, it may still be worth exploring for UAM navigation (Fitts & Seeger, 1953; Meng & Spence, 2015; van Erp, 2007). Overall, further research is necessary to validate specific design recommendations for vibrotactile navigational feedback in multimodal UAM displays.

5 Limitations

Virtual reality simulations have been shown to enhance ecological validity and improve the generalizability of experimental findings, though this simulation may not fully capture the sensory and cognitive demands that UAM operators are likely to encounter in real-world operations. For example, aircraft physics such as drift, turbulence, and vibration were not present and could influence the experience (Böck et al., 2024). Additionally, UAM flights will likely involve more complex task demands than the one presented in this experiment. Further studies should include unexpected ATC directives, mid-air conflict resolution, and the presence of additional aircraft. Additionally, with only 24 participants, statistical power and generalizability is limited. The data from novice participants may not reflect the performance or preferences of trained UAM operators. Also, only subjective measures (e.g., NASA TLX) were used to assess workload. Physiological indicators such as heart rate variability or eye tracking could have provided objective insights. Moreover, tactors were attached to a vest which was worn over participants' clothing items, so tactor intensity varied depending on the thickness and number of clothing items participants wore. This may account for variability in post-experiment user feedback items regarding comfort and intensity. Finally, due to the within-subjects experimental design, repeated exposure to the flight paths and procedures may have influenced results across conditions due to learning or familiarity.

6 Conclusion

The present findings demonstrate a clear benefit of directional vibrotactile navigational cues for the UAM operations tested. Directional cues were associated with shorter correction times during the en route phase and fewer path deviations across flight phases, supporting their potential utility in future UAM cockpits. Based on these results, directional vibrotactile cues appear well-suited to enhance multimodal UAM displays by providing intuitive, nonvisual navigational guidance during critical phases of flight.

However, given the variability observed during the glideslope flight phase, future research should assess the effectiveness of these displays under increased operational demands: during landing, while managing communications, or in more complex environmental conditions. Additionally, further research is needed to refine vibrotactile navigational display designs for UAM operations. Graded vibrotactile intensities and compatibility with existing mental models of similar systems should be considered. Future work should optimize the effectiveness of vibrotactile navigational displays for different flight phases and workload conditions. Overall, integrating vibrotactile navigational feedback holds promise for improving UAM operator performance and overall flight safety.

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References

1. Ahuja, S., Strybel, T.Z., Vu, K.-P.L., Marayong, P., Shankar, P., Battiste, V.: Development and validation of a virtual UAM transportation system. In: Proceedings of the International Symposium of Aviation Psychology (2023).
2. Antcliff, K.R., Moore, M.D., Goodrich, K.H.: Silicon Valley as an early adopter for on-demand civil VTOL operations. In: 16th AIAA Aviation Technology, Integration, and Operations Conference (2016). https://doi.org/10.2514/6.2016-3466
3. Bijjahalli, S., Sabatini, R., Gardi, A.: GNSS performance modelling and augmentation for Urban Air Mobility. Sensors 19(19), 4209 (2019). https://doi.org/10.3390/s19194209
4. Böck, H., Appel, P.B., Eisenmann, L.M., Kaiser, L., Riener, A.: Exploring turbulence impact on passenger experience in Urban Air Mobility: Insights from a virtual reality study. In: 2024 IEEE Intelligent Vehicles Symposium (IV), pp. 3114–3119 (2024). https://doi.org/10.1109/iv55156.2024.10588742
5. Cholewiak, R.W., Brill, J.C., Schwab, A.: Vibrotactile localization on the abdomen: Effects of place and space. Perception & Psychophysics 66(6), 970–987 (2004). https://doi.org/10.3758/bf03194989
6. Community, B.O.: Blender - a 3D modelling and rendering package. Stichting Blender Foundation, Amsterdam (2018). http://www.blender.org
7. Cooper, G.E., Harper, R.P.: The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. Report No. ASD-TR-76-19 (1969).
8. Grier, R.A.: How high is high? A meta-analysis of NASA-TLX global workload scores. In: Proceedings of the Human Factors and Ergonomics Society 59th Annual Meeting, pp. 1727–1731 (2015).
9. Haas, J.K.: A history of the Unity game engine (2014).
10. Haneji, K., Leung, K., Tran, A., Cheung, J., Deabaapilux, W., Marayong, P., Vu, K., Shankar, P., Strybel, T.Z., Battiste, V.: Use of tactile alerts in Urban Air Mobility Vehicles. In: Praetorius, G., Sellberg, C., Patriarca, R. (eds.) Human Factors in Transportation. AHFE International Conference (2023).
11. Hart, S.G., Staveland, L.E.: Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In: Advances in Psychology, pp. 139–183 (1988). https://doi.org/10.1016/s0166-4115(08)62386-9
12. Jones, L.A., Ray, K.: Localization and pattern recognition with tactile displays. In: 2008 Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (2008). https://doi.org/10.1109/haptics.2008.4479910
13. Lu, S.A., Wickens, C.D., Sarter, N.B., Sebok, A.: Informing the design of multimodal displays: A meta-analysis of empirical studies comparing auditory and tactile interruptions. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting 55(1), 1170–1174 (2011). https://doi.org/10.1177/1071181311551244

14. Meng, F., Spence, C.: Tactile warning signals for in-vehicle systems. Accident Analysis and Prevention 75, 333–346 (2015). https://doi.org/10.1016/j.aap.2014.12.013
15. United Nations: World urbanization prospects: the 2018 revision. United Nations, San Francisco, CA, USA (2018).
16. Nguyen, T.: Dynamic delegated corridors and 4D required navigation performance for Urban Air Mobility (UAM) airspace integration. Journal of Aviation/Aerospace Education & Research (2020). https://doi.org/10.15394/jaaer.2020.1828
17. Rupert, A.H.: An instrumentation solution for reducing spatial disorientation mishaps. IEEE Engineering in Medicine and Biology Magazine 19(2), 71–80 (2000). https://doi.org/10.1109/51.827409
18. Stanton, N.A., Young, M.: A Guide to Methodology in Ergonomics: Designing for Human Use. Taylor & Francis, London (1999).
19. Strybel, T.Z., Battiste, V., Marayong, P., Shankar, P., Viramontes, J., Nguyen, H., Cheung, J.: Preliminary validation of a virtual UAM vehicle and simplified cockpit interface. In: Abstract presented at Human Factors & Ergonomics Society 66th International Annual Meeting, Atlanta, GA (2022).
20. Strybel, T.Z., Battiste, V., Vu, K.-P.L., Marayong, P., Schmitz, M.L., Cheung, J., Culver, C., Alfaroarevalo, A., Shankar, P.: Evaluation of voice vs. text communication modes in simulated UAM operations. In: AHFE International Conference on Human Factors in Design, Engineering, and Computing (2024). In press.
21. Taylor, R.M.: Situational Awareness Rating Technique (SART): the development of a tool for aircrew systems design. In: Situational Awareness in Aerospace Operations (AGARD-CP-478), pp. 3/1–3/17. NATO-AGARD, Neuilly Sur Seine (1990).
22. The Federal Aviation Administration: Urban Air Mobility (UAM) Concept of Operations v2.0. https://www.faa.gov
23. Thipphavong, D.P., Apaza, R.D., Barmore, B.E., Battiste, V., Burian, B.K., Dao, Q.V., Feary, M.S., Go, S., Goodrich, K.H., Homola, J.R., Idris, H.R., Kopardekar, P.H., Latcher, J.B., Neogi, N.A., Ng, H.K., Oseguera-Lohr, R.M., Patterson, M.D., Verma, S.A.: Urban Air Mobility Airspace Integration Concepts and Considerations. NASA (2018).
24. van Erp, J.B.F.: Tactile displays for navigation and orientation: Perception and behaviour. Utrecht University (2007).
25. van Erp, J.B.F., Kroon, L.C., Mioch, T., Paul, K.I.: Obstacle detection display for visually impaired: Coding of direction, distance, and height on a vibrotactile waist band. Frontiers in ICT 4 (2017). https://doi.org/10.3389/fict.2017.00023
26. Vascik, P.D., Hansman, R.J.: Scaling constraints for Urban Air Mobility Operations: Air Traffic Control, ground infrastructure, and noise. In: 2018 Aviation Technology, Integration, and Operations Conference (2018). https://doi.org/10.2514/6.2018-3849